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ANALYSIS PLAN FOR 1985 LARGE-SCALE TESTS

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Technical Report

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20. ABSTRACT *(Continue on reverse side if necessary and identify by block number)*
The purpose of this effort is to assist DNA in planning for large-scale (upwards
of 5000 tons) detonations of conventional explosives in the 1985 and beyond time
frame. Primary research objectives were to investigate potential means to in-
crease blast duration and peak pressures. This report identifies and analyzes
several candidate explosives. It examines several charge designs and identifies
advantages and disadvantages of each. Other factors including terrain and multi-
burst techniques are addressed as are test site considerations.

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SECTION 1
GENERAL

1.1 INTRODUCTION

This effort has been accomplished for DNA under Contract Number DNA001-82-C-0044. The purpose of this effort is to assist DNA in planning for large-scale (upwards of 5000 tons) detonations of conventional explosives in the 1985 and beyond time frame. Primary research objectives were to investigate potential means to increase blast duration and peak pressures. This report identifies and analyzes several candidate explosives. It examines several charge designs and identifies advantages and disadvantages of each. Other factors including terrain and multiburst techniques are addressed as are test site considerations.

1.2 CANDIDATE EXPLOSIVES

Many commercially available explosives were identified and examined for possible application. A few with some advantages over ANFO have been selected as candidates and are presented in Section 2. Army and Air Force R&D organizations were contacted to determine if there were new or unique explosives that might be appropriate for use. There were none; however, other commercial contacts were identified through these organizations. It was hoped that candidate explosives might solve the dilemma of providing significant increases in blast duration; however, this was not the case. The only item that appears promising in this area is the addition of aluminum powder to ammonium nitrate emulsions. There is belief in the blasting industry that this will increase the blast duration; however, there are no tests or data available to confirm this. Also aluminum is expensive and its addition to blasting agents significantly increases the price.

1.3 CHARGE DESIGN

There have been several tests of the more commonly used designs such as spheres, hemispheres, and cylinders. All three of these designs are acceptable and each has some advantages in certain situations. Testing of other designs has been limited to that done by BRL and DNA in the past. No recent testing of other charge designs could be found. Several discussions were held with people from FCDNA, AFWL, and S^3 to elicit their views on charge

designs other than the sphere, hemisphere, and domed cylinder. They pointed out that new and different designs present problems concerning prediction, reproducibility, and rarefaction which may not be evident until after testing has been done at some considerable expense. Higher and narrower domed cylinders appear to enhance peak overpressures; however, this may be at the expense of pressure duration. Hemispheres have promise for increased pressure duration. Details of charge design are discussed in Section 3.

1.4 TERRAIN CONSIDERATIONS

Much of the work in this area has been empirical although some small charge testing has been done to confirm the calculations. Increasing slopes tend to increase peak pressures and decreasing slopes the converse. Some significant pressure increases are possible with slopes of 25 to 40 degrees. The basic problem with using slopes with such angles is finding them or constructing them. Section 4 discusses this issue in more detail.

1.5 MULTIBURST TECHNIQUES

Simultaneous or near-simultaneous detonation of two or more charges in close proximity to each other generates regions of unusually high overpressures. The problems with trying to use this technique are: first, the detonation simultaneity is crucial to the test with little margin for error; second, only a very limited area of enhanced overpressures is available; and third, rarefaction is a significant problem. Rarefaction is the generation of unwanted secondary shock waves in addition to the initial shockwave. Section 5 discusses the multiburst technique in more detail.

1.6 TEST SITE CONSIDERATIC

Large charge detonations of the order of 5000 tons and more will have relatively far reaching effects. Blast, shock waves, and sound will travel well beyond effects from our 600-ton detonations — the largest by DNA to date. There are only two known locations that are reasonably capable of detonating such large events: White Sands Missile Range (WSMR) AND Nevada Test Site (NTS).

The Trinity nuclear detonation (16 July 1945) and several 600-ton conventional detonations have been executed at WSMR. The latest 600-ton detonation was executed on 16 September 1981 and another is planned for late 1983. DNA has established a permanent testing location at WSMR south of Stallion

Control Center. Discussion with Mr. A. Johnson and L. Meadows at WSMR indicates a reticence to consider allowing such large charges to be detonated there. Environmental considerations are important. In addition to deer, antelope, and oryx populations in the area there is the McDonald Ranch (2 miles from the DNA Test Site), now listed in the National Historic Register. Funds have been allocated recently to stabilize what remains of the ranch house and ancillary buildings. The present test site is too close to the ranch to permit detonations much over 600 tons. Also, surrounding communities, particularly Tularosa, must be considered. Under less than ideal atmospheric conditions even 600-ton shots have a very real potential to do damage in these communities. Charges 10 times as large could produce significant damage. According to Sandia National Laboratories (J. Reed) who monitored off-site impacts on DISTANT RUNNER, "even 6000 tons of ANFO would have only just exceeded the damage threshold at Tularosa but not at Alamagordo or other communities." Atmospheric conditions for the DISTANT RUNNER shot were near-ideal. Thus very large detonations would have to have ideal atmospheric conditions. It may be appropriate to plan for intermediate size detonations, of the order of 1800 tons, before larger shots. This would give responsible personnel at WSMR the necessary confidence and data base to proceed with the larger tests.

NTS was the site for numerous atmospheric nuclear detonations between 1951 and 1962. Although there have been no surface detonations of large magnitude since 1962 the location should be capable of handling the 6000- to 15,000-ton detonations of conventional explosive now contemplated. Experience has shown that costs at NTS are significantly higher than at WSMR with a factor of 2 to 3 higher not unrealistic.

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SECTION 2
CANDIDATE EXPLOSIVES

2.1 INTRODUCTION

Various DOD agencies and commercial explosives manufacturers were contacted to determine what was available for consideration. DOD agencies included the US Army's ARADCOM (Lou Avrami, Dover, NJ, 201-328-2512), the US Air Force's Frank Silver Laboratories (Dr. John Wilkes, USAF Academy, 303-472-2655), and the Test Directorate, Field Command, DNA. DOD contractors contacted included PAI, PI, and SRI. Commercial manufacturers included Woodward Explosives, Estancia, NM; Atlas Powder Company, Dallas, TX; Monsanto Company, St. Louis, MO; IRECO Chemicals, Salt Lake City, UT; and Gulf Oil Explosives, Denver, CO.

The various blasting agents which have merit are discussed in the succeeding paragraphs. Advantages and disadvantages are presented to the extent that they are known. Cost information is presented for most candidates; however, it must be emphasized that:

1. Cost information is in 1982 dollars.

2. Most manufacturers quote one price over the phone but indications are that serious discussion about ordering very large quantities could influence the price per pound.

3. Cost information for new blasting agents may be subject to significant change.

2.2 ANFO

ANFO, as used by DNA for large charge detonations, is a mixture of 94-percent ammonium nitrate (AN) and 6-percent fuel oil (FO). It is formed into prills in the manufacturing process that are then coated with a surfactant to reduce moisture absorption ANFO is quite hygroscopic and must be protected from moisture of any kind. Even small amounts of water in ANFO will significantly reduce detonation parameters. Figure 2-1 shows a typical effect. Prill density is usually 1.4 to 1.5 g/cc which gives the ANFO an overall density of 0.78 to 0.90 g/cc. Higher prill densities are also produced as fertilizer grade AN, but densities over 1.7 g/cc make it difficult to absorb the fuel oil (Reference 2). ANFO densities above 0.90 g/cc are possible using techniques such as special manufacturing processes
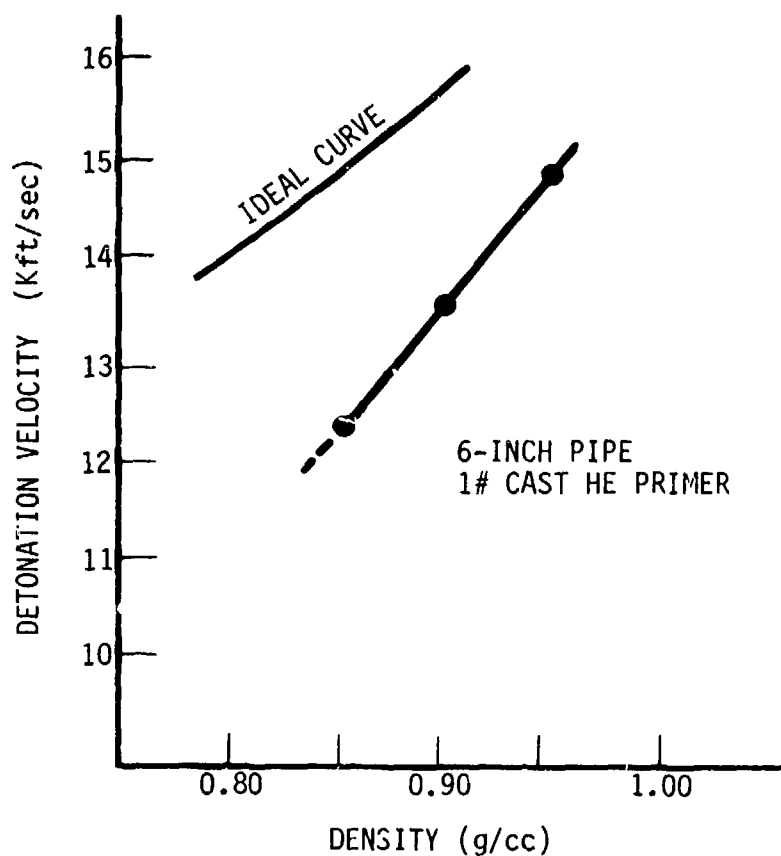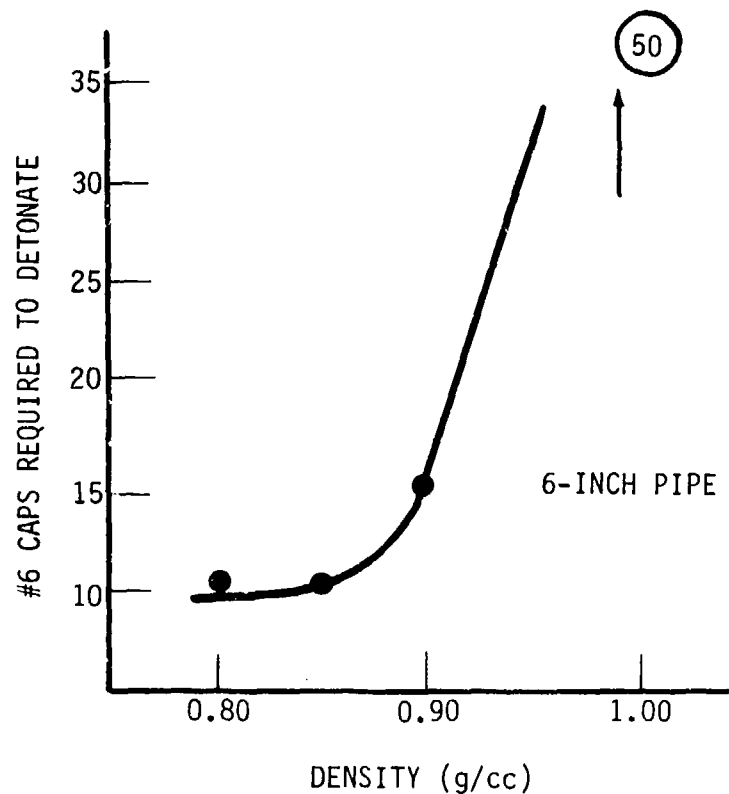
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Figure 2-2. Rate change with density.

Figure 2-3. Change in initiation sensitivity with density.
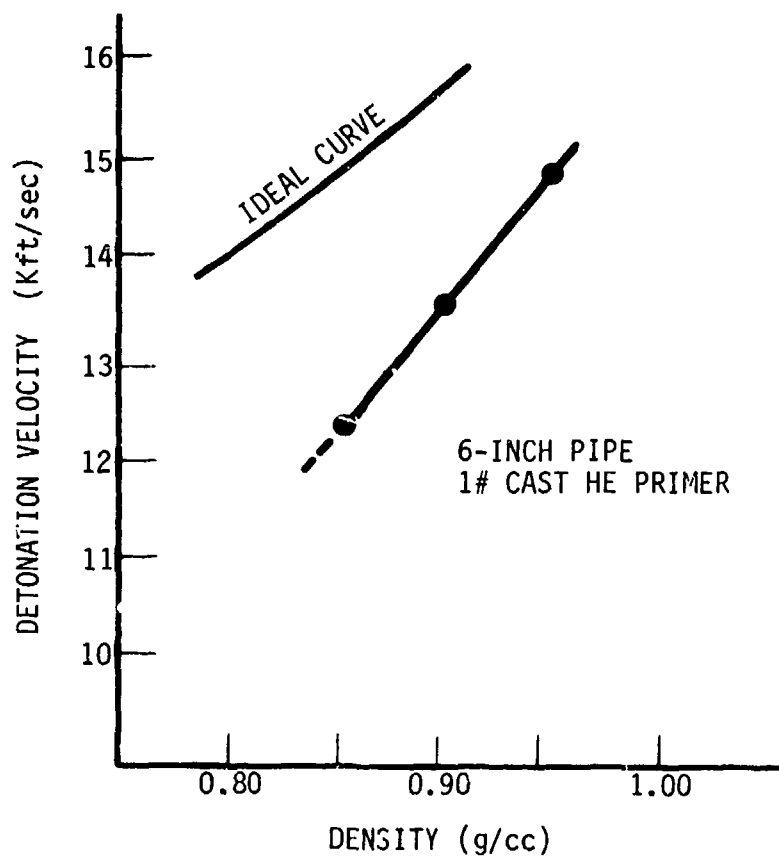
10

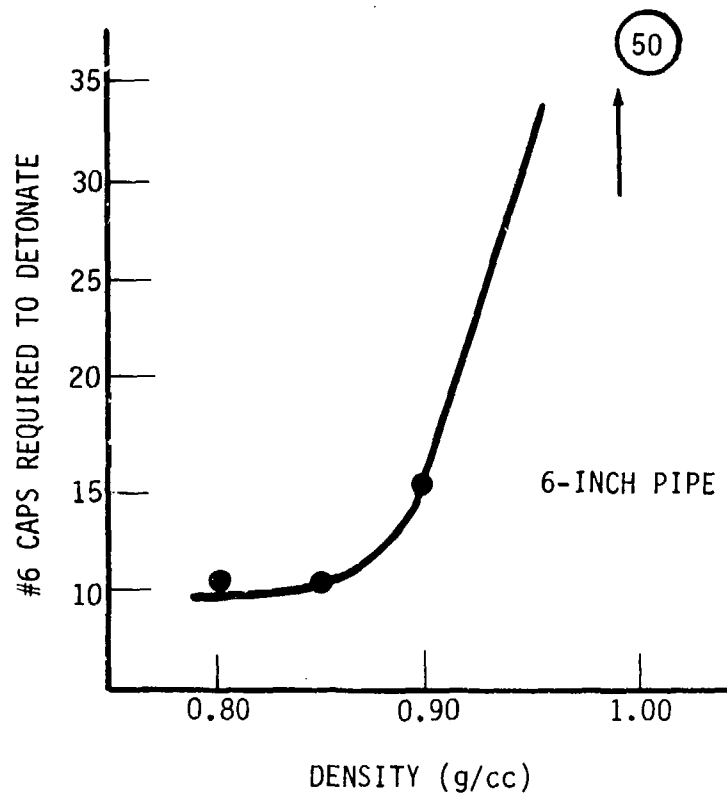Figure 2-2. Rate change with density.

Figure 2-3. Change in initiation sensitivity with density.

ANFO is classified as a blasting agent, not an explosive, and as such is relatively safe to manufacture, store, transport, and handle. It is regarded insensitive to No. 8 blasting caps; it is fairly stable; it is insensitive to temperature change; it cannot be detonated by sparks; it is insensitive to impact (bullets or dropping); and it will not explode if engulfed in flames.

2.2.1 Bulk (Loose) ANFO

Bulk ANFO has been used in several experimental tests to develop ANFO characteristics since 1969. The largest test was 100 tons of bulk ANFO in a hemispherical shape detonated in 1969 at DRES, Alberta, Canada. A fiberglass shell was used to contain the ANFO.

Bulk ANFO can be manufactured at a permanent plant or at the field location where it is to be used. Most manufacturers have portable equipment that will allow spraying of the ammonium nitrate prills with the fuel oil at any designated location. The components are bulk-shipped separately and mixed on site providing a safety advantage in transportation over premixed ANFO.

Bulk ANFO is slightly cheaper than bagged ANFO because of the added labor and cost of bags for the latter. However, bulk ANFO must be containerized to give it the desired shape and to protect it from the elements. The container is a significant portion of the ANFO cost. For DIRECT COURSE the bulk ANFO is expected to cost approximately 17 cents per pound and the reinforced spherical fiberglass container approximately $305,000, or 25 cents per pound of ANFO. The container cost alone is almost 1-1/2 times the cost of the ANFO. For a 2000-ton domed cylindrical container, Mesa Fiberglass, Inc. estimates about 19 cents per pound of ANFO. Container thickness for 2000 tons would be three inches assuming a 3 to 1 safety factor.

The container needed for bulk ANFO can present its own problems. Recent experience with Pre-DIRECT COURSE, a 3-ton HOB event using containerized bulk ANFO, revealed that the container appeared to delay shock wave break out and to distort the shock wave.

Bulk ANFO is hygroscopic, thus it must be protected from moisture, including high humidity conditions. This dictates a closed container or adequate covering for open containers used for bulk ANFO events. Because ANFO will absorb moisture from the air, bulk ANFO will desensitize slowly with time. Most manufacturers recommend it be used within 2 weeks. Another concern with bulk ANFO is the tendency of the fuel oil to evaporate out of the

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ANFO, thus reducing its percentage below 6 percent. Monsanto Company conducted tests of this by regularly sampling an open bin of ANFO. They found that during summer months the ANFO could lose up to 3 percent fuel oil in just one week (Reference 4). A reduction of fuel oil by 3 percent would significantly reduce detonation velocities, and peak overpressures. Figure 2-4 shows the effect on detonation velocities.

Large charges using bulk ANFO will normally have an appreciable stack depth. For example, a 6000-ton charge in the shape of a domed cylinder (L/D = 0.75) would be roughly 80 feet high with a 63-foot diameter. The compression effect on the ANFO in the stack would cause a density variation from the bottom to the top of the stack. Since detonation velocity is a function of density this could present a problem in achieving a uniform blast wave from the bottom to the top of the stack. Although no direct density measurements of stacks have been made, there is some limited data available on velocity measurements from the DICE THROW and MILL RACE events.

Figure 2-4. Velocity change with oil content.

These data indicate that detonation velocities increase linearly from the top to the bottom of the stack (within the cylindrical section) with differences being as high as 700 m/sec (~15 percent) for 600-ton domed cylinders (References 6 and 7). Large charges may require sequential detonation of boosters to remedy this phenomenon.

Table 2-1 summarizes properties of bulk ANFO.

Table 2-1. Properties of bulk ANFO.

Composition: 94% AN, 6% FO

Density: 0.80 to 0.90 g/cc

Detonation Velocity: 5000 m/sec

Available Energy: 912 cal/g

Classification: Blasting Agent

Cost: $.36 per pound ($.17 for the bulk ANFO and $.19 for the container)

Remarks:

1. ANFO is easy and safe to handle, store, and transport.
2. Bulk ANFO is very hygroscopic.
3. In worst case conditions bulk ANFO can lose half its fuel oil content to evaporation in 7 days.
4. Bulk ANFO requires a container to obtain the desired stack geometry.
5. Density, and thus detonation velocity, varies slightly as a function of stack depth.

2.2.2 Bagged ANFO

Most testing (both ANFO characterization testing and effects testing) has been done using bagged ANFO. Several 120-ton events and two 600-ton events have been executed during the 1970s and early 1980s. Some problems were experienced in stack integrity and one of the pre-DICE THROW stacks actually fell down when partially constructed. That led to a revised stacking plan for the ANFO bags and no further problems have been encountered.

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Whether or not large domed cylinders of 1800 tons and up can be safely stacked remains somewhat questionable.

Most manufacturers prefer to use their permanent facilities to produce bagged ANFO. The bags are then transported to the detonation site and stacked int: the desired shape.

Bagged ANFO costs approximately 18 cents per pound to manufacture including the cost of the bags at 20 cents each (50-1b size). In order to compare costs with other candidates, most of which require containerization, the cost of stacking the bags must be included for an ANFO application. Stacking costs for MILL RACE were about $86,000 including the cost of the temporary shelter. This is about 7 cents per pound of ANFO. Thus the net cost of bagged ANFO rises to approximately 25 cents per pound.

Bagged ANFO is well protected from absorption of moisture from the air; however, rain or snow could present a significant moisture problem. Bagged ANFO should be protected from inclement weather in storage, transport, and stacking operations. Limited experimentation has been done to determine fuel oil loss from bagged ANFO. NSWC set aside five 50-pound ANFO bags at MISERS BLUFF on 17 August 1978. They then sampled the bags for six days consecutively and found that net fuel oil loss averaged about 20 percent over the first 2 to 3 days and then essentially ceased (Reference 8). Independent tests by Monsanto Company on bagged ANFO also showed that a 20-percent loss in the first 2 to 3 days is common (Reference 9).

The bulk ANFO discussion above on density variations with stack depth applies equally to bagged ANFO. In fact on two events, DICE THROW and MILL RACE, good velocity data were obtained on bagged ANFO. The conclusion is that ANFO is compressible and higher densities are realized towards the bottom of the stack. Thus higher detonation velocities will be evident towards the bottom of the stack.

Of some concern in using bagged ANFO for very large charges is the stacking time and the stability of the stack. It took six days to construct the 600-ton cylinder for MILL RACE (twelve 10-hour shifts) (Reference 6). A 6000-ton cylinder could take several weeks to construct by using these figures. This would be unacceptable as the ANFO would deteriorate to poor quality during such an extended time period. Revised stacking procedures to

complete the job in less than two weeks would need to be devised. The mechanical safety of an 80-foot high stack is also open to question although knowledgeable people at NSWC believe it would be possible to build an 80-foot stack using glued ANFO bags. However, there are questions remaining such as framing methods that need to be examined in detail with experts in the construction business.

Table 2-2 summarizes data for bagged ANFO.

Table 2-2. Properties of bagged ANFO.

Composition: 94% AN, 6% FO

Density: 0.80 to 0.90 g/cc

Detonation Velocity: 5000 m/sec

Available Energy: 912 cal/g

Classification: Blasting Agent

Cost: $.25 per pound ($.18 for the bulk ANFO and $.07 for stacking costs)

Remarks:
1. ANFO is easy and safe to handle, store, and transport.
2. Bagged ANFO is slightly hygroscopic.
3. In worst case conditions bagged ANFO can lose 20 percent of its fuel oil content in 2 to 3 days. The fuel oil content seems to stabilize at this point.
4. Approximately one percent of the stack weight will be paper bag material.
5. Density, and thus detonation velocity, varies slightly as a function of stack depth.

2.3 APEX 1360 (REFERENCES 10 AND 12)

This is one of several blasting agents manufactured by Atlas Powder Company. It was selected to show the effect of adding aluminum. Atlas makes several variations with different amounts of aluminum depending on the customers needs. In general the higher the aluminum content, the higher the price.

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APEX 1360 is 80-percent ammonium nitrate, 7-percent aluminum, and 13-percent mineral oils and water (see Table 2-3). It is a thick liquid emulsion that is classified as a blasting agent, thus it is as insensitive and safe as ANFO. Its density of 1.25 g/cc is much higher than that of ANFO which would reduce the volumetric size of a stack by 36 percent for any given slack tonnage.

Table 2-3. Properties of APEX 1360*.

```
Composition:   80% AN, 7% Aluminum, 13% Mineral Oils
               and Water (liquid emulsion)

Density:  1.25 g/cc

Detonation Velocity:  7000 m/sec

Available Energy:  875 cal/g

Classification:  Blasting Agent

Cost:  $.84 to .89 per pound ($.65 to .70 for the
       emulsion and $.19 for the container)

Remarks:
  1. APEX 1360 is easy and safe to handle, store, and
     transport.
  2. Consistency is similar to light grease.
  3. Addition of aluminum should increase blast dura-
     tion but no data is available.
  4. APEX 1360 is nonhygroscopic and it can be stored
     for several weeks with no degradation.
```

APEX 1360 would be produced at one of the manufacturer's permanent facilities and then transported by truck or rail to the detonation site. It does not degrade with time and can be stored for several weeks with no detrimental effects on performance. The APEX product line is not sensitized by pumping under high pressure and can be pumped upwards of 200 feet easily.

_____

*Manufactured by Atlas Powder Company.

APEX 1360 has been used in high volume for years by the blasting industry and is well characterized. It is not hygroscopic nor will it separate out into nonuniform consistency when poured into a tank. Its cost in 1982 was 65 to 70 cents per pound in large quantities. The added cost for a holding tank would make the total cost 84 to 89 cents per pound of emulsion. The tank material is not a limiting factor as this product is insensitive to metal, fiberglass, and other construction materials. As discussed in the paragraph on bulk ANFO, the need for a container may be a disadvantage since recent evidence suggests that such a tank would slow shock wave break out and may distort the shock wave.

One alternative is to bag the APEX 1360 and stack it as we currently stack bagged ANFO. The grease-like consistency of APEX 1360 is such that it may be possible to do this safely. Filling of voids may be difficult, however. This would eliminate the container cost and add a bagging cost which would reduce the overall cost by approximately 12 cents per pound.

This blasting agent is relatively expensive in comparison to ANFO. The primary reason for this increase is the addition of aluminum which should increase the duration of the blast wave. Although none of the manufacturers who use aluminum in their blasting agents could quantify it, they agreed that the duration should be greater with the addition of aluminum. In theory the aluminum takes longer to burn than the ANFO because it does not have a built in oxidizer as does the ANFO. The aluminum must use oxygen from the air or from the ammonium nitrate. Thermodynamically, the aluminum significantly increases the specific detonation energy of the explosive.

2.4 NITRIC ACID AND NITROPROPANE (REFERENCES 13 AND 14)
This is a relatively new mixture that has been developed by Joseph L. Trocino and Associates, Sherman Oaks, CA. Its primary advantages are its cost and use of readily available ingredients. Its detonation parameters have been investigated by SRI and some insensitivity testing has been done by China Lake.

The mixture has a water-like consistency and in this form would require a container to hold it. However, additives are available to obtain a gel-like consistency at some undetermined increase above the 30 cents per pound estimated basic cost. The gel may have application because in bagged form it should be possible to stack it like bagged ANFO without a holding container.

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Pouring loose gel between the bags in each layer as we now do with ANFO may not be feasible because of its viscosity and flow characteristics.

There is concern over a fiberglass container's use with this candidate. The separate ingredients may react with the fiberglass while being poured or at some later time. An insensitive spray-on coating may be required inside the container such as DUPONT's viton coating. This would increase the cost of the container somewhat above the currently estimated 19 cents per pound of explosive. As with other candidates which need a container, the container may delay shock wave break out and distort the shock wave somewhat based on preliminary findings from pre-DIRECT COURSE.

The mixture contains 51.02-percent nitric acid and 24.05-percent nitro-propane by weight. The remainder is water. The nitric acid used is a common industrial product called Baume 42 and is readily available. The ingredients would be transported separately and mixed on site if a containerized system were employed. If a gel were used it would most probably be packaged at a plant remote from the site and shipped to the site.

SRI, in testing for DNA, has determined some properties of the mixture. Its ideal detonation pressure is 133 kbars. Some additional properties are available from SRI. China Lake has accomplished limited sensitivity testing. The mixture is impact insensitive and similar to nitromethane in the card gap test. Nitric acid concentrations above 67 percent by volume (the proposed mixture is 69.23 percent) will detonate when subjected to a blasting cap, so this mixture cannot be classified as a blasting agent.

From Table 2-4 it can be seen that this mixture has a high density, 1.25 g/cc, and a relatively high detonation velocity, 6480 m/sec. SRI does not ex-pect that its blast wave duration would be significantly different from ANFO's, given the same tonnage.

Once the ingredients have been combined the resulting mixture appears to be satisfactorily insensitive for storage and transportation safety and is not subject to degradation in storage — for at least 3 weeks and perhaps much longer.

Table 2-4. Properties of nitric acid and nitropropane.

Composition: 51.02% HNO_3, 24.05% Nitropropane, 24.93% H_2O (by weight)

Density: 1.25 g/cc

Detonation Velocity: 6480 m/sec

Available Energy: 908 cal/g

Classification: Not classified

Cost: $.49 per pound ($.30 for the mixture and $.19 for the container)

Remarks:

1. Components would be mixed on site by the contractor.

2. Nitric acid type is Baume 42 which is a common industrial grade.

3. Mixture is insensitive, nonhygroscopic, and does not degrade with time (2 to 3 weeks).

4. Container may require special coating to protect it from ingredients.

5. Handling HNO_3 requires protective clothing and self-contained breathing apparatus.

6. Consistency is like water; however, additive can be used to make a gel at some increased cost.

7. As a gel it may be possible to bag this mixture and stack it without a container.

2.5 NITROPROPANENITRATE (NPN) (REFERENCE 11)

NPN is patented by John R. Post, General Energy Company. PAI has recently done characterization work on it for DNA. NPN is a blasting agent with an ammonium nitrate base and additives of nitropropane, methanol, and methocel. Table 2-5 provides specific data. Note that its available energy is high yet its detonation velocity is relatively low. This might indicate that this blasting agent will have a relatively long blast wave duration.

NPN can be mixed in the field at the site where it is to be used. AN prills are crushed and the fuels are added. The methocel, an antimigratory agent, prevents separation of the components once mixed. Depending on the prill crushing process the density of the NPN can vary from 1.05 to 1.3 g/cc.

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Table 2-5. Properties of nitropropanenitrate (NPN).

Composition: 86.8% Ammonium Nitrate, 6.5% Nitropropane,
6.5% Methanol, 0.2% Methocel

Density: 1.2 g/cc

Detonation Velocity: 5180 m/sec

Available Energy: 1180 cal/g (preliminary)

Classification: Blasting Agent

Cost: $.45 per pound ($.26 for the NPN and $.19 for
the container)

Remarks:

1. Components would be mixed on site by the contractor.

2. Methanol and nitropropane have low flash points and
are hazardous before they are mixed into NPN.
Handling requires self-contained breathing apparatus.

3. Mixture is insensitive, nonhygroscopic, and does not
degrade with time.

4. Consistency is like slush. It may be possible to bag
NPN and stack it without using a container.

Commercial grain crushers will provide a density of 1.05 g/cc. More careful crushing and packing will provide the higher densities. Velocity is directly proportional to density.

As with other candidate blasting agents, the consistency of NPN may allow it to be bagged and stacked without a support structure. The advantages of this are in cost and absence of a structure that could affect the blast wave. The capability to bag it inexpensively and the type of bag needed are unknowns.

NPN is nonhygroscopic, insensitive, and does not readily degrade with time once it is mixed, according to PAI. However, two of its ingredients, nitropropane and methanol, are considered hazardous. They have relatively low flashpoints (47.5 and 60°F respectively) and self-contained breathing apparatus must be worn while handling them. Once mixed with the other ingredients to form NPN these two ingredients are no longer hazardous.

This blasting agent may have value if it can provide a long duration shock wave, particularly if it can be mixed and bagged at a manufacturer's facility. This latter point would eliminate hazardous materials handling in the field.

2.6 DBA-22M (REFERENCES 15 AND 16)

This blasting agent is one of many made by IRECO Chemicals, Salt Lake City, UT. The producer has the capability to vary the percentages of ingredients depending on the application. This particular agent is heavy in aluminum content. It contains 50-percent ammonium nitrate, 35-percent aluminum, 14-percent water, and 1-percent gums. From Table 2-6 it can be seen that the available energy is very high and the detonation velocity is lower than that of common ANFO. This suggests that it would have a relatively long shockwave duration. Testing would be necessary to confirm this.

Table 2-6. Properties of DBA-22M*.

Composition: 50% Ammonium Nitrate, 35% Aluminum, 14% Water,
               1% Gums

Density: 1.5 g/cc

Detonation Velocity: 5000 m/sec

Available Energy: 1420 cal/g

Classification: Blasting Agent

Cost: $.78 to $.88 per pound ($.59 to $.69 for the DBA-22M
       and $.19 for the container)

Remarks:
 1. Components can be mixed on site.
 2. Mixture is insensitive, nonhygroscopic, and can be stored
    up to 3 weeks after mixing.
 3. Consistency is similar to soft rubber. It may be pos-
    sible to bag it and eliminate the need for a container.

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*Manufactured by IRECO Chemicals.

The density of this agent is 1.5 g/cc which is almost twice that of ANFO. This agent would require a volume only 60 percent of that for ANFO for the same tonnage; but the cost of this agent makes it noncompetitive with other candidates unless pressure duration is an overriding consideration. It is 3 to 4 times as costly as bagged ANFO.

2.7 HARDENING EMULSION (References 15 AND 16)

This blasting agent is a new one, just developed by IRECO Chemicals. From Table 2-7, it is similar to ANFO except that 4 percent water and emulsifier has replaced 4 percent of the ammonium nitrate from the ANFO composition. The blasting agent has special additives which make it harden in a matter of hours, depending on the volume involved. The material becomes hard enough to machine it. This increases the possibilities as far as forming and manufacturing shapes. First unusual shapes could be formed using a container that could then be removed leaving just the blasting agent. Also sections or pieces of more common shapes such as hemispheres, spheres,

Table 2-7. Properties of a hardening emulsion*.

Composition: 90% Ammonium Nitrate, 6% Fuel Oil, 4% Water, and Emulsifier

Density: 1.2 g/cc

Detonation Velocity: 6000 m/sec

Available Energy: Unknown

Classification: Blasting Agent

Cost: $.40 to $.50 per pound (cost does not include cost of container used to hold the emulsion until it hardens).

Remarks:
1. Components can be mixed on site.
2. Mixture is insensitive, nonhygroscopic, and can be stored for several weeks with no degradation.
3. Liquid emulsion hardens to the point it is machinable.
4. Container can be of inexpensive material and is reusable.

*Manufactured by IRECO Chemicals.

or cylinders could be molded in the plant, shipped to the site where the charge is to be built, and assembled like building blocks. Alternatively, a container could be built at the site, the liquid agent poured in, and when hard, the container could be removed. The hardened emulsion is self-supporting and may be left in place for two to three weeks if necessary. It is insensitive, nonhygroscopic, and will not degrade with time.

This blasting agent has a high density making its volume requirement substantially less than that for the same tonnage of ANFO. It also has a higher detonation velocity than ANFO. Although detailed energy calculations have not been made, they are expected to show a higher value than that for ANFO.

A very large quantity of this blasting agent, such as 6000 tons, would have to be poured in layers, allowing each layer to cool and harden before pouring the next layer. Otherwise a void or "carrot" could develop in the middle of the tank as the emulsion hardens, since it does shrink slightly as it hardens. There may be some way to pour it all at once and insure no voids. The time needed to pour 6000 tons is about 3 days unless layer hardening is necessary. In this case the total time would depend on the thickness of each layer poured and its hardening time. This is an unknown at present.

This blasting agent has not been tested extensively or characterized as yet. Its cost of 40 to 50 cents per pound makes it almost twice as expensive as bagged ANFO but competitive with other candidates.

2.8 NCN-600 (REFERENCE 19)

This blasting agent is one of a large product line produced by Gulf Oil Chemicals Company. They produce ANFO, ammonium nitrate slurries, and aluminized mixtures. NCN-600 was selected because it has a very high density, detonation velocity, and total energy (see Table 2-8). It can be purchased in bulk or bagged form; however, the cost of 33 cents per pound as shown in the table is for the bagged product.

This product appears to be significantly superior to ANFO in every category: density, velocity, and energy. It also has the added advantage of being nonhygroscopic. The cost is only 33 percent higher than ANFO. However, there may be a significant disadvantage in that it may be difficult to stack. The product sets up to a self-supporting gel shortly after being bagged. This would make it difficult to fill the voids between the bags of each

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Table 2-8. Properties of NCN-600*.

Composition: Nitro - Carbo - Nitrate

Density: 1.3 g/cc

Detonation Velocity: 6000 m/sec

Total Energy: 1148 cal/g

Classification: Blasting Agent

Cost: $.33 per pound ($.26 for the NCN-600 and $.07 for stacking costs).

Remarks:

1. May be bagged or shipped in bulk.

2. Consistency is a gel that holds its shape when the bag is removed.

3. Bags are 9-inches diameter and 33-inches long (cylindrical) and weight 50 pounds.

4. NCN-600 is insensitive, nonhygroscopic, and can be stored for several weeks with no degradation.

layer. Also the style bags used are long cylindrical bags that do not lend themselves to stacking as do ANFO bags. These problems may have reasonable solutions. For example if a few bags in each layer were cut open the pressure from subsequent layers would probably squeeze the gel into any voids. The cylindrical bags now used for NCN-600 might be exchanged by Gulf for a bag that is shaped like the ANFO bags so that they would stack well.

2.9 CANDIDATE EXPLOSIVES SUMMARY

ANFO has served us well these past several years. It's inexpensive and superior in many respects to TNT, its predecessor. However, ANFO is very hygroscopic and also has a distinct tendency to lose 15 to 20 percent of its fuel oil in less than a week. It has a relatively low density compared to other candidates and thus must be stacked higher or use a larger container than other candidates.

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*Manufactured by Gulf Oil Chemicals Company.

For very large charge applications some of the candidate explosives have advantages over ANFO. Aluminized mixtures should be able to provide improved pressure duration over ANFO. Also NPN has the potential to increase the pressure duration. However, since little data is available for the aluminized agents or NPN, testing is necessary.

Although other candidates have higher detonation velocities and thus will probably generate higher peak pressures, it is believed that this improvement would be at the expense of pressure duration. The peak pressures from a 6000-ton shot should be far beyond that needed by the most ardent experimenter; however, the pressure duration will not increase commensurately. Therefore, this study has prioritized pressure duration over peak pressure.

The need for a container is a disadvantage for any candidate because of the added cost and possible impact on the shock wave. However, some of the candidates (APEX 1360, DBA-22M, and NCN-600) are now bagged in polyethelene containers and the others probably could be bagged with little problem. Bag shapes used and agent consistency would have to be amenable to stacking.

SECTION 3
CHARGE DESIGN

3.1 INTRODUCTION

Designs for high explosives to accurately simulate nuclear detonations
have evolved over several years beginning as early as 1948 when the Ballistic
Research Laboratories (BRL) experimented with different charge shapes. Most
high explosives detonations through the mid 1960s used TNT. As TNT became
more expensive, alternate explosives came into use, primarily nitromethane
and ammonium nitrate-based blasting agents. The powder and liquid composi-
tion of these agents forced the use of holding containers or bags to obtain
the desired charge shapes.

Many charge shapes have been tried with varied success. In general the
more complex the shape is, the more difficult it is to predict or reproduce
the effects (air blast, ground shock, and cratering). Designs used in recent
years have been primarily hemispherical, spherical, or domed cylinder. The
domed cylinder is a vertical right cylinder with a hemispherical cap on the
top. These three shapes provide predictable and reproducible effects plus
the air blast shock wave is fairly clean and exponentially decaying.
Rarefaction — the production of unwanted secondary shock waves — is
minimized or eliminated with these three designs.

3.2 BACKGROUND

In 1948 BRL experimented with several charge shapes to determine the
variation in peak pressure. Shapes tested included the sphere, cylinder,
hollow cylinder, cube, flat plate, and the cone. They observed the rarefac-
tion phenomena but did not pursue it in their report. At close ranges they
found increased pressures and impulses off the corners (45 degrees) of the
cylinders and cubes and directly away from the face of the flat plate. They
also found that at extended ranges the charge shape became unimportant as
pressures and impulses were similar for all shapes of the same charge
weight.

In late 1967, DASA hired General American Research Division to conduct
blast directing tests. The scheme is shown in Figure 3-1. The charges were

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REACTION ZONE
(CONTAINS HIGH EXPLOSIVE
OR DETONABLE GAS)

TEST POINT

PORTION OF 1-DIMENSIONAL
FLOW FREE OF REFRACTION
EFFECTS

R_o

TEST POINT
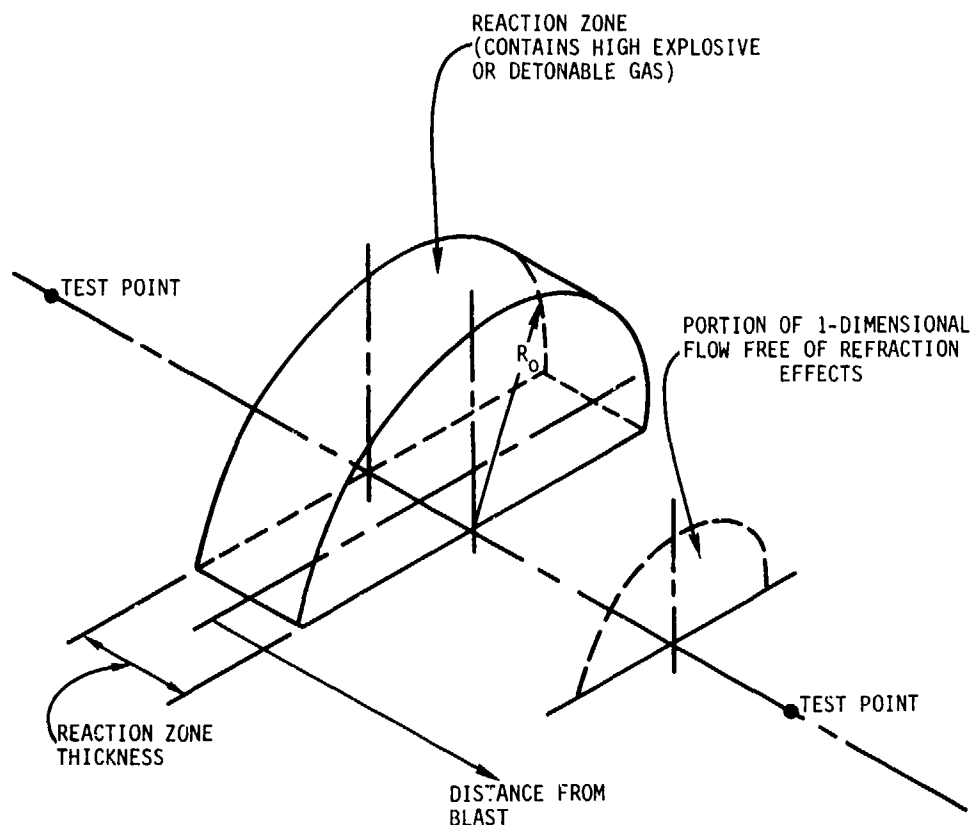
REACTION ZONE
THICKNESS

DISTANCE FROM
BLAST

Figure 3-1. Blast directing scheme.

in the shape of a hemispherical thin plate which detonated simultaneously at all points. Over-pressures twice those for spherical charges of the same weight were obtained perpendicular to the plate face at close ranges. Also a half-conical zone, shown in the figure, experienced rarefaction-free air blast.

The development by DNA of ANFO as a useful simulant for nuclear effects was begun in 1969 at DRES, Alberta, Canada. It proceeded through many tests using primarily hemispherical, spherical, and cylindrical designs culminating in the pre-DICE THROW and DICE THROW events in 1975. This development is well documented in a report, "ANFO History and Uses," in final draft being published by Kaman Tempo for DNA. In essence, the hemisphere and sphere were discarded in favor of the domed cylinder for surface detonations. The

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relationship between air burst, ground shock, and cratering of the domed cylinder scaled well to a nuclear event.

Anomalies in the blastwave such as jetting were a problem with large charges constructed with TNT. The change to ANFO and close control of charge construction have materially reduced this problem. It is believed that voids in the charge, nonsymmetry and nonsimultaneous initiation of the b osters, contribute to anomalies in the blastwave.

The use of spherical designs has continued application, however, in height-of-burst (HOB) events where the explosives are suspended i ove ground. DNA is currently planning to conduct such an event of 600 tons in late 1983. A spherical 20-ton HOB calibration test was successfully executed at White Sands Missile Range on 7 October 1982.

3.3 DESIGN CONSIDERATIONS

Charge design for large charges must consider several factors. First the design must be attainable in the field (ie, it must be able to be constructed safely). The concept for initiating the explosives must also be attainable such that an unreasonable number of detonating points is not a requirement. Second the charge design performance should be predictable and reproducible. Modeling techniques should be capable of predicting detailed effects such as crater size, ground shock, and air overpressure as a function of distance. Charge shapes which are symmetrical about the vertical axis (spheres, hemispheres, vertical cylinders) are relatively easy to model and predict. Designs which are not symmetrical about the vertical axis are much more difficult to model and predict. Third the design must be reasonable in cost to accomplish. Unusual shapes are inherently more costly to model, predict, and construct. The need for a container must be factored into the cost of the design since for large charges the cost for a container can be a significant portion of the cost of the explosives. For example, the container for the DIRECT COURSE event is expected to cost $305,000. It will hold 600 tons of ANFO. Container cost for this event will be $.25 per pound of ANFO. Fourth, the design must eliminate or minimize rarefaction — the generation of secondary shock waves which detract from and distort the primary shock wave. Discontinuities in the charge shape such as sharp corners are the more obvious conditions that cause rarefaction. Symmetrical shapes such as spheres, hemispheres, and cylinders essentially eliminate rarefaction. Designs such as cubes or similar shapes with sharp discontinuities

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on the surface will normally cause severe rarefaction at close ranges. At
extended ranges these separate shock waves have a tendency to combine into a
single wave. Thus, at extended ranges charges with the same tonnage look
similar regardless of their shape.

3.4 SPHERICAL CHARGES

A well constructed spherical charge can be one-point detonated at the
center and produce a clean airblast wave. Effects are predictable and repro-
ducible. It is the simplest design and the easiest to model. Its disadvan-
tages are twofold. First, it does not provide a good ratio of airblast,
ground shock, and cratering effects compared to a nuclear detonation. Second,
it is more difficult to construct, normally requiring a container of some
sort to obtain the desired shape. The container adds to the cost and can af-
fect the waveforms and the break-out time of the shock front.

3.5 HEMISPHERICAL CHARGES

Hemispherical charges are similar to spherical charges in several re-
spects. They can be one-point detonated to produce predictable and repro-
ducible effects. The airblast wave is normally quite clean and exponentially
decaying. They are of simple design and are easily modeled. If bagged explo-
sives are employed a holding container is not required to produce the desired
shape. Hemispherical charges have one disadvantage: they produce too large a
crater and ground shock in comparison to the airblast effect. Some observers
and experimenters also indicate that these charges throw ejecta (dirt, rocks,
etc) to substantial distance, endangering the experiments on the test. The
hemisphere may increase pressure duration, however, because its radius for
any given explosive weight is almost 50 percent greater than the domed
cylinder.

3.6 NATURAL SLUMPING CHARGES

A modification of the hemispherical design that would be less costly to
construct is the use of a bulk agent such as ANFO in a naturally slumping
form. A low restraining container around the bottom part of the pile and
leveling of the top of the pile would provide a rough hemispherical shape.
This design, although less expensive than others, would have to be tested to
determine waveforms and resolve questions about rarefaction.

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3.7 DOMED CYLINDERS

Extensive testing of cylinders was done in the pre-DICE THROW shots. Various length-to-diameter (L/D) ratios were tested both with and without hemispherical caps (domes). It was found that an L/D of 0.75 to 0.84 was optimum for providing a good ratio between air blast, ground shock, and cratering. The DICE THROW (1975), MISERS BLUFF (1978), MILL RACE (1981), and DISTANT RUNNER (1981) events used the domed cylinder design with bagged ANFO as the blasting agent. All had an L/D of 0.75.

NSWC also tested cylinders with various L/D ratios in the mid 1970s. They found that for close-in ranges peak pressures 1.5 to 1.8 times as high as for comparable tonnage spheres were obtained for long thin cylinders. Figure 3-2 is extracted from their report and shows this phenomenon. To place the Scaled Distance from the figure in perspective, a scaled distance of 5 would be 531 feet from ground zero and a scaled distance of 10 would be 1062 feet from ground zero on a 600-ton event. Thus, on a 600-ton event an
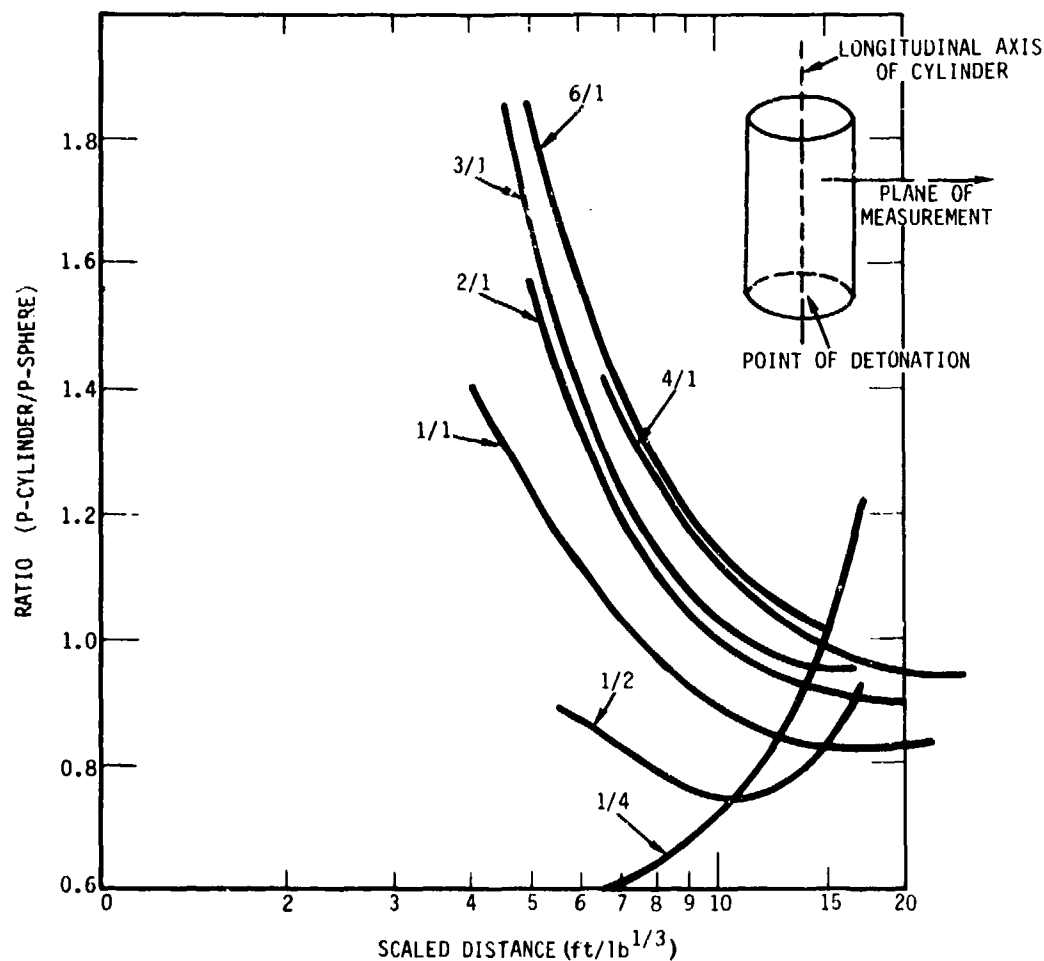

Figure 3-2. Ratio of free air peak overpressure (P-cylinder/P-sphere) versus distance for cylinders with differing aspect ratios.

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experiment 531 feet from ground zero would see a peak pressure of 335 kPa
rather than 203 kPa* if a cylinder with L/D = 3 were used instead of one with
an L/D = 0.75. This is a significant increase if, in fact, these ratios hold
true for large charge events.

3.8 CHARGE DESIGN SUMMARY

Results of tests of designs other than the three discussed above show
that all have disadvantages which outweigh their advantages. Problems with
prediction of effects, reproducibility, and rarefaction are the biggest con-
cerns. Based on research to date there does not appear to be any merit in
further investigating other shapes at this time. The only charge design vari-
ation that may have merit is the domed cylinder with a much larger length-to-
diameter ratio (L/D) than the 0.75 L/D being used presented by DNA. The ad-
vantage is apparently a reinforced pressure regime at close-in ranges as dis-
cussed above. The disadvantages are that cratering ground shock and probably
pressure duration will be reduced. Discussion with representatives of Mesa
Fiberglass, Inc., who constructed the pre-DIRECT COURSE shell, indicates that
tall, thin domed cylinders are not particularly difficult to construct. A
domed cylinder (L/D = 3) holding 6000 tons of ANFO, for example, would have a
diameter of about 43 feet and a height of 152 feet to the top of the dome.

Although increasing the L/D ratio will apparently improve peak pressures,
it will probably reduce pressure durations. The burn time of the ANFO in the
cylinder will be shortened because the radius is reduced. Thus a dichotomy
seems to exist. Design changes to improve peak pressure have a negative ef-
fect on pressure duration and vice versa. Figure 3-3 shows pressure duration
versus range for four events: DRES Event III (100 tons), MISERS BLUFF II-1
(120 tons), DICE THROW (628 tons), and MILL RACE (600.19 tons). All used
ANFO. Note that duration increases with charge size. Thus we should expect
an increase well above these values by using very large charges in the order
of 6000 tons. It should also be possible to enhance the duration even more
by going to a hemispherical design rather than a domed cylinder design. For
a given tonnage the ANFO burn time should be longer because the radius of a
hemisphere is larger than the radius of a domed cylinder. For example, a
6000-ton domed cylinder (L/D = 0.75, ρ = 0.9 g/cc) has a radius of 31.5
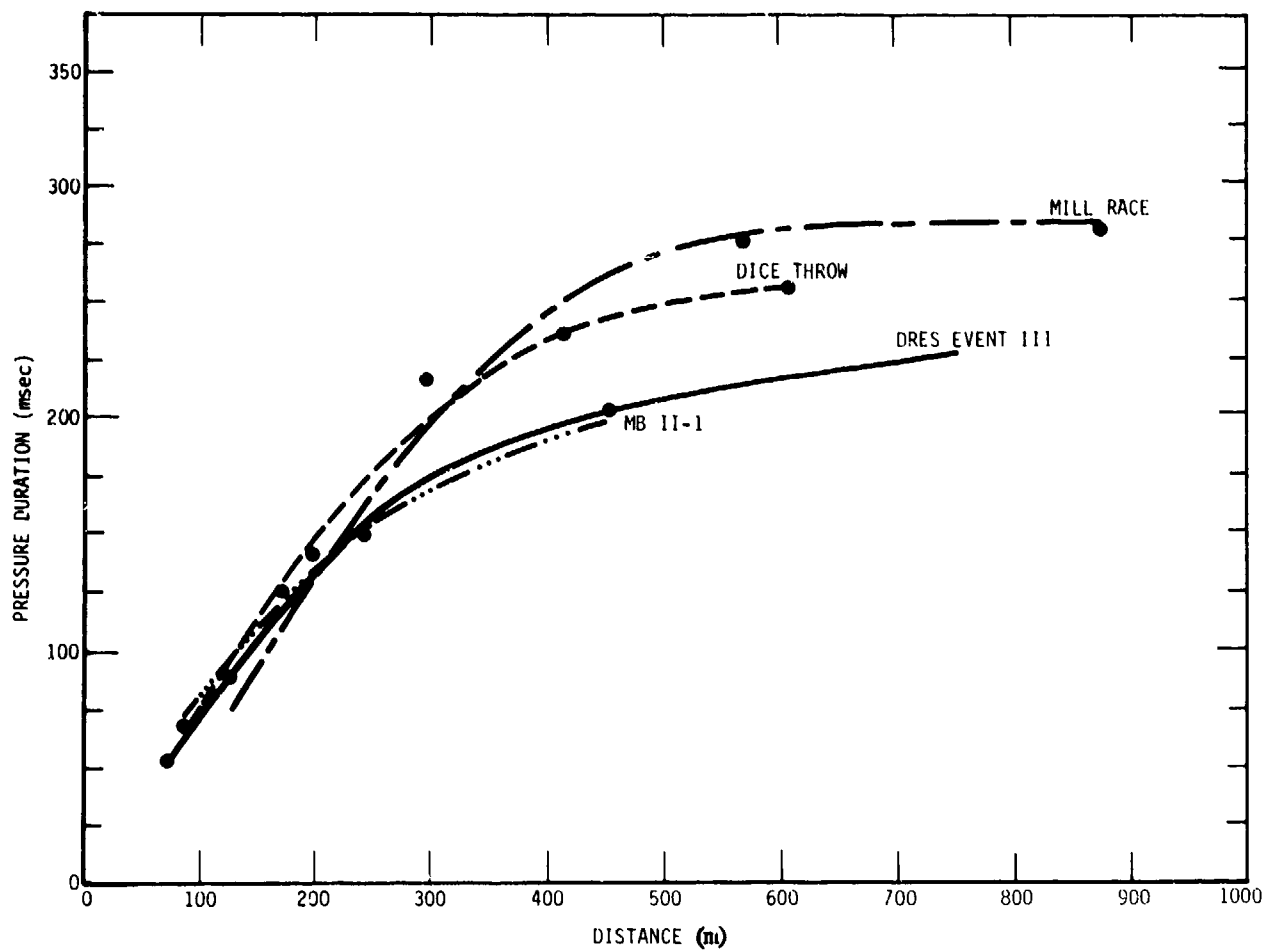
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*Data taken from MILL RACE.

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Figure 3-3. Pressure duration versus distance for selected events.

feet, while a 6000-ton hemisphere has a radius of 46.8 feet, an increase of almost 50 percent.

SECTION 4
TERRAIN EFFECTS

4.1 INTRODUCTION

In an uncontrolled environment, terrain effects present a difficult problem in determining pressure differentials at various locations. The many interactions create a variety of interposing pressure waves. The USA Ballistic Research Laboratory did some work in this area published as ARBRL-CR- 00364. This report also included theoretical data for controlled terrain environments.

4.2 DISCUSSION

It is known that rising slopes create an enhanced pressure in the shock front and falling slopes a reduced pressure. Depending on the slope angle a "Mach reflection" or a "regular reflection" of the shockwave can occur. Figure 4-1 shows these two conditions plus the one for a falling slope. Figure 4-2 shows increases in pressure (above incident overpressure) for slope angles up to 40 degrees. A "Mach reflection" is created at these lower angles. As the slope angle increases above 30 degrees there is a transition zone to about 40 degrees, above which "regular reflection" takes place. Figure 4-3 shows the pressure increases for angles above 30 degrees assuming "regular reflection." As can be seen from the figures, at angles of 30 degrees and higher, significant pressure increases are attainable, according to the Whitham Theory. Some small charge experimentation has been carried out which shows increases somewhat less than the theoretical values for the higher incident overpressures (Figure 4-4).

One possible way to take advantage of this effect is to construct a ramp and place the experiment at the top of the ramp at the desired distance from ground zero (GZ). However, rarefaction effects caused by the sides of the ramp create unwanted pressure variations and subsequent pressure pulses. This condition is also difficult to forecast or to reproduce consistently. Another possibility is to use a valley where the sides have a relatively constant slope of 10 to 30 degrees on both sides of the bottom. Figure 4-5 is a prediction, using the Whitham Theory, of pressure increases possible for

A. FALLING SLOPE — DIFFRACTION

B. RISING SLOPE — REGULAR REFLECTION
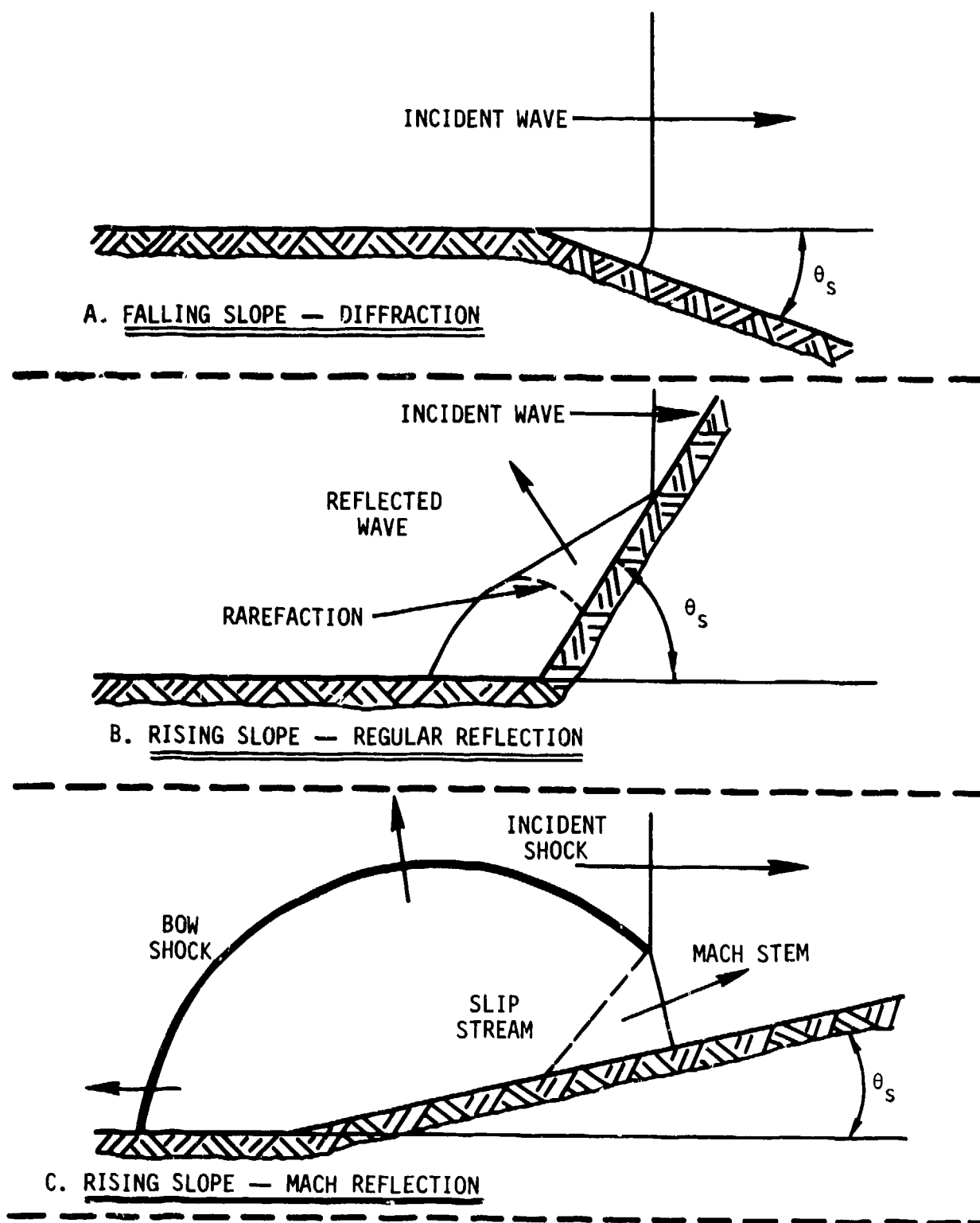
C. RISING SLOPE — MACH REFLECTION

Figure 4-1. Changes in shockwave patterns caused by changes in terrain.
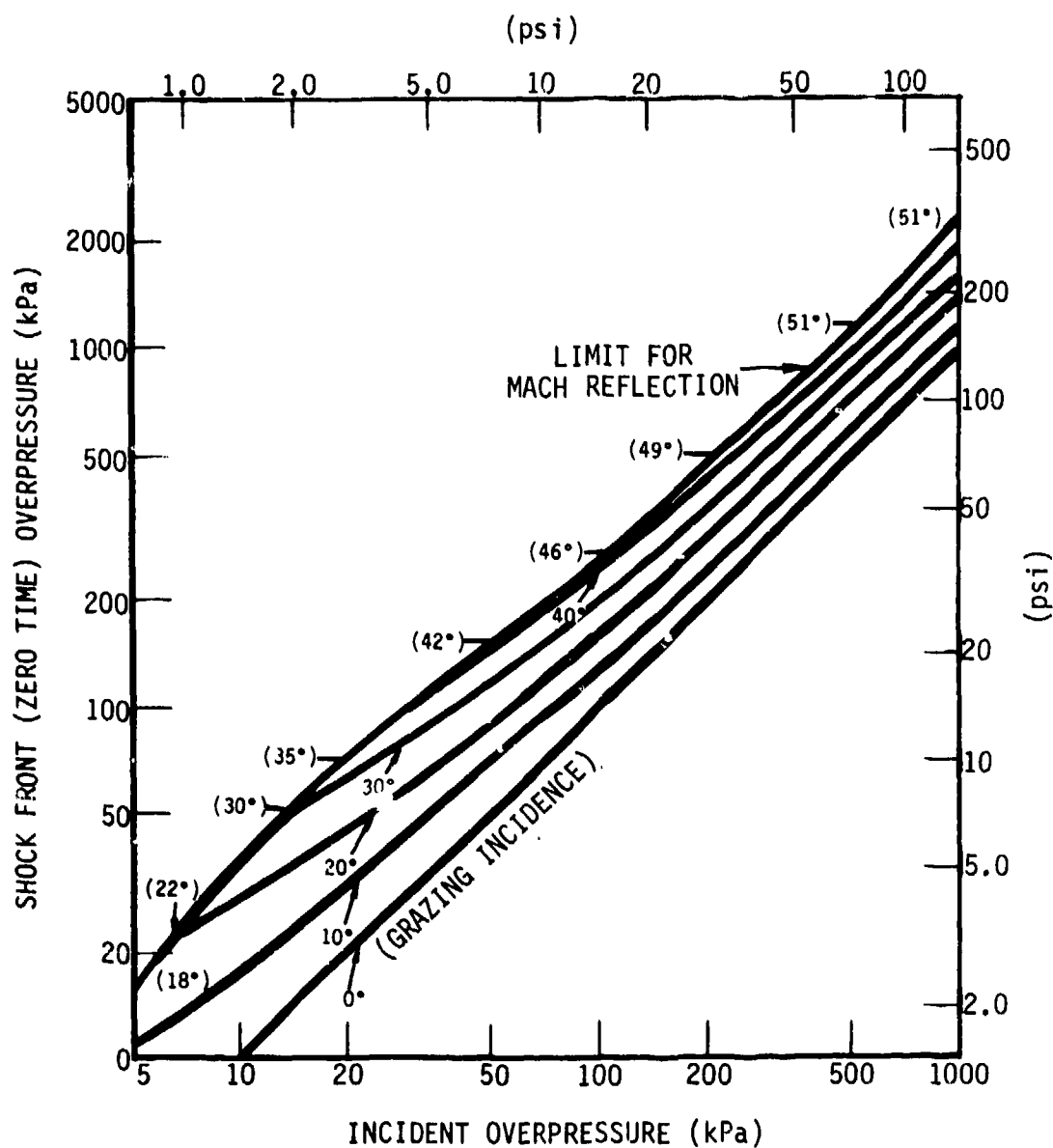
Figure 4-2. Overpressure at the shock front on a rising slope
(reflected overpressure) versus peak incident
overpressure for shockwaves undergoing Mach
reflection. From Whitham Theory.

Note: Numbers in parenthesis identify extreme
(limit) slope angles along the "Limit for Mach
Reflection" line. Other numbers on the figure
identify the slope angles to which each curve
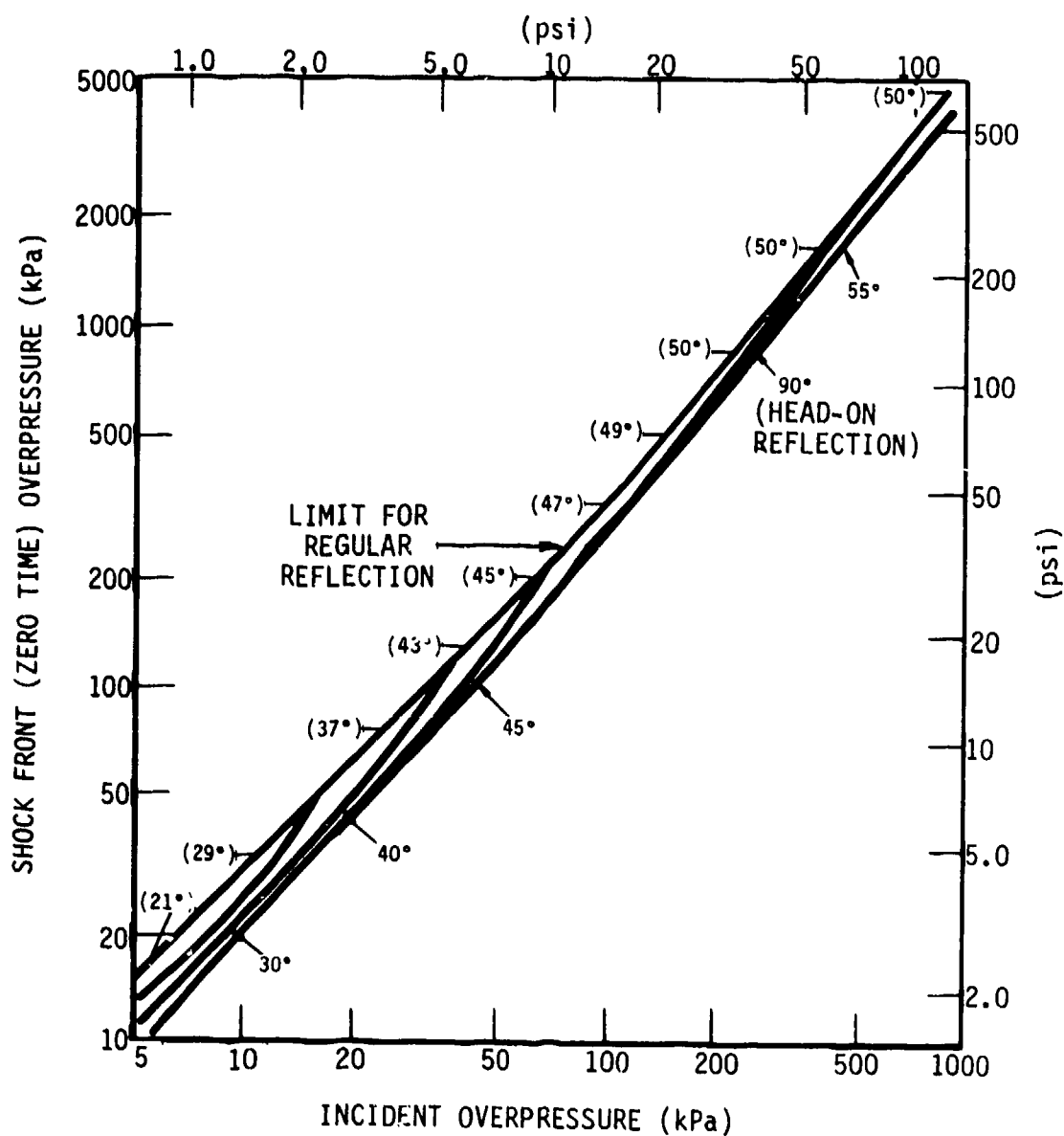applies.

Figure 4-3. Overpressure at the shock front on a rising slope (reflected overpressure) versus peak incident overpressure for shockwave undergoing regular reflection.

Note: Numbers in parenthesis identify extreme (limit) slope angles along the "Limit for Regular Reflection" line. Other numbers on the figure identify the slope angles to which each curve applies.
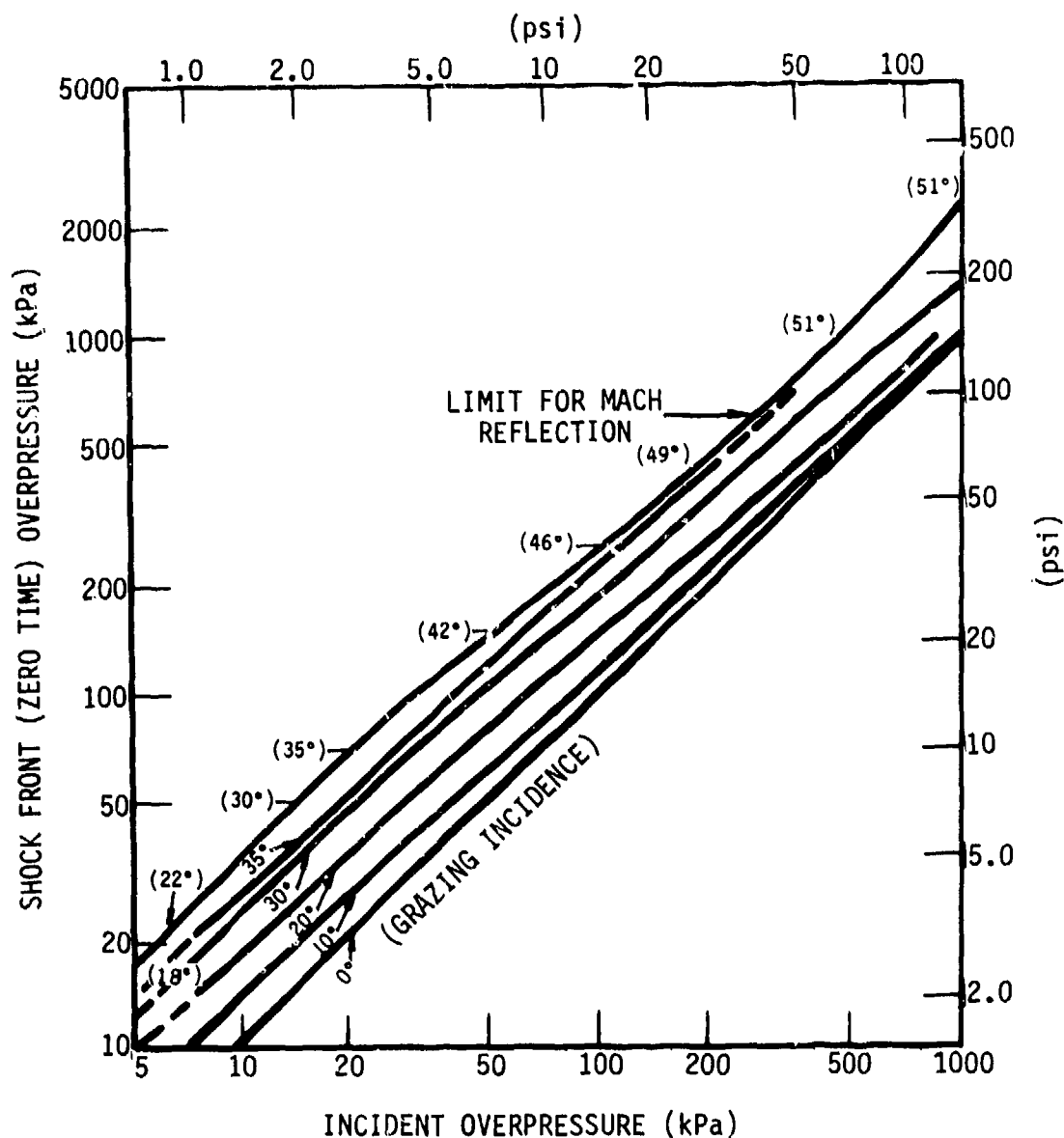
Figure 4-4. Overpressure at the shock front on a rising slope (reflected overpressure) versus peak incident overpressure for shock-waves undergoing Mach reflection. From Small Charge Studies.

Note: Numbers in parenthesis identify extreme (limit) slope angles along the "Limit for Mach Reflection" line. Other numbers on the figure identify the slope angles to which each curve applies.
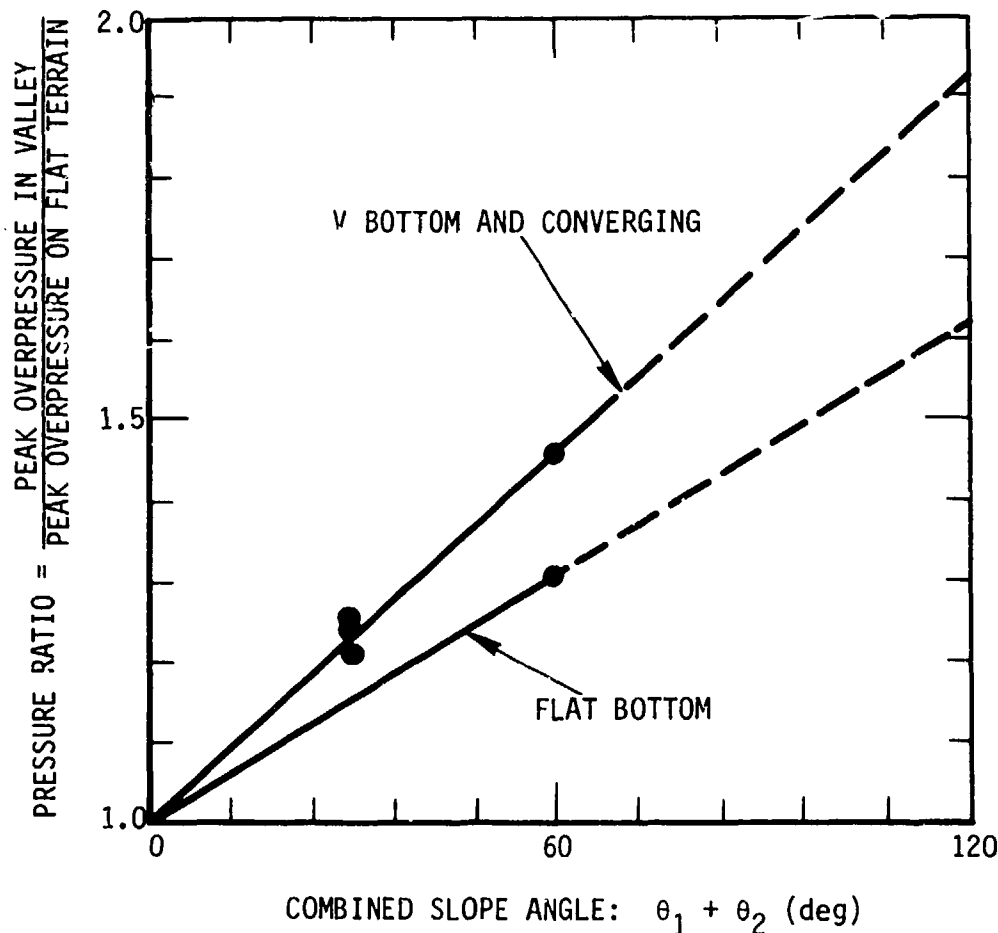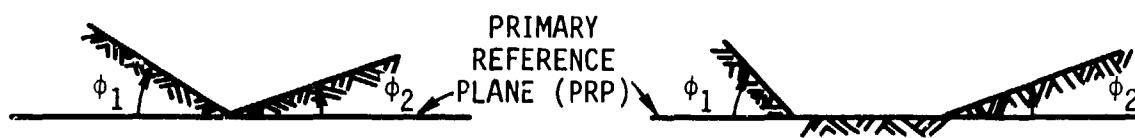
Figure 4-5. Average peak pressure ratio at the bottom of valleys as a function of combined slope angle.

varying slopes. Again significant improvement in peak pressure appears possible.

A third possibility is use of a large depression in the earth such as Sedan crater at the Nevada Test Site (NTS). The crater's side slope is approximately 28 degrees and it is generally uniform in shape. The conical shape should increase peak pressure differentials beyond those for simple slopes (Reference 20).

4.3 TERRAIN EFFECTS SUMMARY

There is little doubt that rising slopes, either manmade or natural, create significant increases in overpressures. The realities of the situation have to be considered, however. Sedan crater, for example, was created by a nuclear detonation and there may be contamination resident in the crater.

Manmade slopes are a possibility; however, the width and length of the slope must be large in comparison with the experiment to negate end effects that create unwanted perturbations in the airblast. Further, such slopes will affect the airblast on each side and behind them as well, forcing the surrounding area to be void of other experiments needing a clean airblast shockwave.

Natural terrain slopes, particularly valleys, are usable to improve peak pressures; however, irregularities in the natural terrain will cause blast-wave perturbations that will present problems. Also the slope would have to be large enough for the experiments and generally of constant angle. It is doubtful that such topography exists at the few locations open to large charge testing. For these reasons this option does not have sufficient merit to warrant further pursuit at this time.

SECTION 5
MULTIBURST TECHNIQUES

5.1 DISCUSSION

The DIPOLE WEST series of shots was the first to investigate multiburst phenomena. A series of 16 shots were fired at varying separation distances, heights of burst, and tonnage. Three of the 16 were single-charge detonations; the remaining 13 were 2-charge detonations. The last four 2-charge detonations were nonsimultaneous. Figure 5-1 shows the effect from a 2-charge, simultaneous detonation. Although the figure is a side view, a similar shock interaction occurs in the horizontal plane as well. In the narrow area on each side of the center line there is only a single shock front while a double shock exists on each side of this area. Obviously the double shock
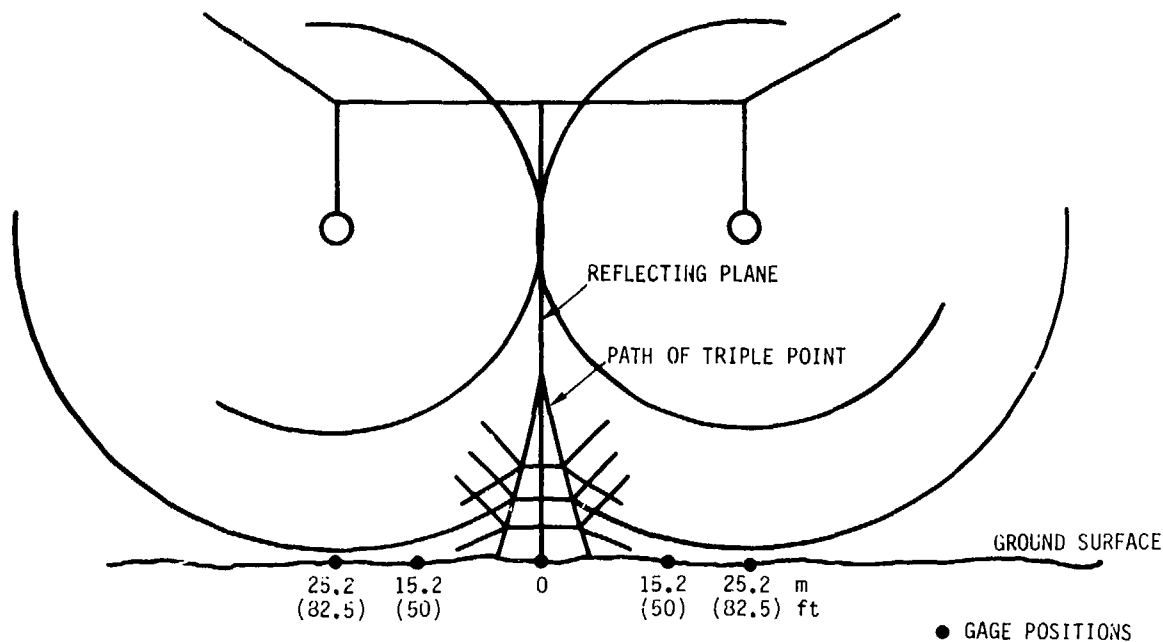

Figure 5-1. Shock interactions for the horizontally-separated, two-charge configuration.

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region is not a good simulation of a nuclear burst. Note that the lines defining the center region are curved, not straight, and for increased ranges this narrow center area becomes larger and larger until it approaches a 180-degree sector. For example, the center area is 50-feet wide at a range of 130 feet when the charges are separately by 50 feet. The same phenomenon occurs on the other side of the burst. Pressures at various ranges in this center region are similar to a one-charge configuration whose tonnage equals the sum of the tonnages of the two charges. Although the usable area at very close ranges is reduced, this concept has the advantage that two small charges can be constructed in place of one large one. This would allow a reduction of charge construction time and reduced stack height. For tonnages of 5 to 15 KT the stack height is a definite consideration. A 6-KT domed cylinder is about 80 feet high assuming the standard L/D of 0.75. This concept has the disadvantage that an unplanned, nonsimultaneous detonation of the two charges would change the triple point path and thus change the shape of the usable area.

The MISERS BLUFF series had three shots where multiple charges were detonated simultaneously, Phase I shot 4 (6 charges), Phase I shot 8 (24 charges), and Phase II shot 2 (6 charges). Only Phase II shot 2 was extensively instrumented to measure air pressures as a function of time — the other two were instrumented for ground motion only. The Phase II shot 2 event created complex waveforms on charge radial lines, on bisector lines, and near the center of the 6-charge array. Apparently one charge detonated slightly after the other five. This suggests that multiple charges beyond a total of two are difficult to control or predict, and may be difficult to reproduce.

5.2 SUMMARY - MULTIBURST TECHNIQUES

Simultaneous detonation of multiple charges is technically possible, given the state of the art. The limitations for simultaneity requirements are within a few tens of microseconds. The penalty if they do not detonate simultaneously is severe. The usable area at high pressure regimes is quite small given just two charges — far less than the 120-degree sector needed. At longer ranges the two charges appear as one anyway with correspondingly more normal pressure regimes. Further pursuit of this technique is not recommended for large charge configurations.

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SECTION 6
CONCLUSIONS AND RECOMMENDATIONS

6.1 CONCLUSIONS

Based on the preceding discussion, the following conclusions are drawn:

- ANFO remains the most inexpensive candidate. Even if a container is required (and ANFO needs a bigger container because of its density) it is less expensive than other candidates.

- Aluminized slurries and possibly NPN have good potential for increasing the duration of the pressure pulse. However, aluminized slurries come in a wide variety of types, percentages of aluminum, and cost. Gulf has an aluminized product selling for $27.25 per 100 pounds that needs to be examined in addition to those discussed in Section 2. (This information was received just prior to finalizing this report.)

- Domed cylinders, particularly high length-to-diameter ratios, optimize peak pressure in the airblast shockwave but it appears that this occurs at the expense of pressure duration of the shockwave. This phenomenon needs more research and probably testing to be proven.

- Hemispheres have larger radius than domed cylinders or spheres for any given explosive weight so their explosive burn time is significantly longer. This should translate to longer pressure durations.

- Shapes such as flatplates or as shown in Figure 3-1 can generate unusually high peak pressures but have disadvantages that outweigh their advantages. Specifically rarefaction problems and difficulty in prediction or reproducibility.

- Terrain, specifically an increasing slope, enhances peak pressures significantly for angles of 30 degrees or more. There is no data on the effect on pressure duration. However, naturally occurring usable terrain would be difficult, probably impossible, to identify in the limited areas available to large charge testing. Construction of such slopes would be high cost and would create rarefaction problems.

- Multiple bursts provide unusually high peak pressures but experience has shown that there are significant rarefaction, prediction, and reproducibility problems.

- There are only two known area in CONUS where charge₃ of
  the magnitude of 6000 tons and up might be detonated:
  White Sands Missile Range and the Nevada Test Site. The
  former may be limited in tonnage because of surrounding
  communities and the environmental impact on the range
  itself.

6.2 RECOMMENDATIONS

The following recommendations are made concerning large charge testing
in the 1985 and beyond time frame:

- That a more detailed analysis of available aluminized
  blasting agents be undertaken. This should be a rela-
  tively short and easily accomplished excursion.

- That a testing program be developed and implemented for
  selected aluminized blasting agents and NPN to determine
  their capability to produce enhanced positive pulse pres-
  sure duration.

- That a testing program be developed and implemented to
  determine whether hemispheres provide a significant ad-
  vantage over domed cylinders or spheres in creating
  longer pressure pulses.

- That an intermediate tonnage event of the order of 1800
  tons be programmed at WSMR prior to larger detonations.
  This will help alleviate concerns about damage to sur-
  rounding communities and the local environment.

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US Army Training and Doctrine Comd
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